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Weak-Wave Analysis of Shock Interaction With a Slipstream

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Summary

A weak-wave analysis of shock interaction with a slipstream is presented. The theory is compared with the acoustic theory and to the exact nonlinear analysis. Sample calculations indicate that the weak-wave theory yields a good approximation to the exact solution when the shock waves are sufficiently weak that the associated entropy increase is negligible. A qualitative discussion of the case of counterflowing streams is also included.

Introduction

When a shock is incident on an interface of relative motion, a wave is usually transmitted through the interface and another wave is reflected. The strengths of these two waves are determined by two boundary conditions: pressure and flow directions are equal on the two sides of the interface both ahead of, and behind, the interaction point. The corresponding problem for sound waves has been solved by both Ribner (ref. 1) and Miles (ref. 2). These solutions corrected earlier erroneous analyses. For shock waves, the changes in flow direction are related to wave strengths in a highly nonlinear way; consequently, solutions are obtained by iteration (as, for example, in ref. 3).

The weak-wave analysis, which is given herein, provides an intermediate solution valid for weak shocks. It yields analytic expressions which are more accurate for shocks than the acoustic approximation. Furthermore, the derivation of the results provides some physical insight into the relationship of the acoustic theory to the full shock wave problem.

The material is presented in the following order. First, the problem is described and the boundary conditions at the interface are given. Then, the results of references 1 and 2 for the acoustic case are summarized. The acoustic results are taken as a first-order approximation for weak shocks, and the weak-wave theory is developed as a correction to this first-order approximation. One way of solving the exact equations is then described and the results of the three theories are compared. Finally, a qualitative discussion of the case of counterflowing streams is given.

Symbols

a	coefficient defined by equation (17b)
b	coefficient defined by equation (17c)
M	Mach number
p	pressure
R	reflection coefficient, defined by equation (35)
T	transmission coefficient, defined by equation (36)
z	parameter defined by equation (10)
β	$= \sqrt{M^2 - 1}$
γ	ratio of specific heats
Δ	change in quantity due to shock or expansion wave
δ	small variation in quantity
ε	$= \frac{\Delta p}{p}$
θ	shock angle
ν	flow deflection angle

Subscripts:

i	incident
r	reflected
T	total
t	transmitted
o	acoustic solution
1,2,3,4,5	region 1,2,3,4,5, respectively (fig. 1)

Analysis

Basic Considerations and Boundary Conditions

If the incident shock is curved, its radius of curvature is assumed to be large relative to the thicknesses of the shock waves and of the slipstream. Consequently, the interaction may be treated as a local phenomenon (assuming negligible shock wave thickness). (See, for example, the interesting schlierens in ref. 4.)

The flow configuration is diagrammed in figure 1. The undisturbed parallel flows in regions 1 and 5 proceed from left to right. A shock i in region 1 is incident on the slipstream, giving rise to a reflected compression or expansion wave r and a transmitted shock t.

The pressures in regions 1 and 5 are equal, as are those in regions 3 and 4. Consequently, the pressure increments through the waves satisfy the relation

$$\Delta p_i + \Delta p_r = (p_2 - p_1) + (p_3 - p_2) = p_4 - p_5 = \Delta p_t \quad (1)$$

Similarly, the changes in flow direction must match on the two sides of the slipstream. Notice, however, that the incident shock deflects the flow downward, whereas a reflected shock tends to deflect the flow upward. Therefore, this latter deflection appears with a negative sign.

$$\nu_i - \nu_r = \nu_t \tag{2}$$

Thus, a reflection expansion produces a negative ν_r.

Equations (1) and (2) are exact within the assumptions of the theory. Approximations enter in converting the pressure increments to shock strengths and in relating the shock strengths to flow deflections.

Acoustic Theory

As was mentioned in the Introduction, the acoustic approximation has been treated independently by Ribner (ref. 1) and Miles (ref. 2). Ribner's treatment is especially interesting in the present context, because he treats the sound waves as Mach waves. However, in the usual acoustic analysis the pressures p_2, p_3, and p_4 represent sinusoidal perturbations on the undisturbed pressure $p_1(=p_5)$, and equation (2) represents a relation between the slopes in a sinusoidal ripple in the slipstream.

Equation (1) is written in the form

$$\frac{\Delta p_i}{p_1} + \frac{\Delta p_r}{p_1} = \frac{\Delta p_t}{p_5} \tag{3}$$

In the acoustic approximation,

$$\nu = \frac{\beta}{\gamma M^2}\frac{\Delta p}{p} \tag{4}$$

Consequently, in this approximation, equation (2) can be written

$$\frac{\beta_1}{\gamma_1 M_1^2}\left(\frac{\Delta p_i}{p_1} - \frac{\Delta p_r}{p_1}\right) = \frac{\beta_5}{\gamma_5 M_5^2}\frac{\Delta p_t}{p_5} \tag{5}$$

If the reflection coefficient is defined by

$$R \equiv \frac{\Delta p_r/p_2}{\Delta p_i/p_1} = \frac{\Delta p_r/p_1}{\Delta p_i/p_1} = \frac{\Delta p_r}{\Delta p_i} \tag{6}$$

and the transmission coefficient by

$$T \equiv \frac{\Delta p_t/p_5}{\Delta p_i/p_1} = \frac{\Delta p_t/p_1}{\Delta p_i/p_1} = \frac{\Delta p_t}{\Delta p_i} \tag{7}$$

equations (3) and (5) become, respectively,

$$1 + R = T \tag{8}$$

$$1 - R = zT \tag{9}$$

where

$$z \equiv \frac{\gamma_1 M_1^2 \beta_5}{\gamma_5 M_5^2 \beta_1} \tag{10}$$

The solution of this set of equations is

$$R = \frac{1-z}{1+z} \tag{11}$$

$$T = \frac{2}{1+z} \tag{12}$$

This acoustic solution represents a first-order solution for weak shocks. Since it is an acoustic approximation, it is independent of wave strength. It also provides other useful information relating to the shock wave solutions. For example, if $z = 1$, then $R = 0$ so that there is no reflection, and the entire wave is transmitted. One such case occurs when the two streams are at the same temperature, there is no relative motion, and $\gamma_1 = \gamma_5$. But it can also occur if there exists a small relative motion provided that there is a compensating difference in the γ's.

Equation (11) indicates that when $z < 1$ the reflected wave is a compression, and equation (12) indicates that the transmitted wave is stronger than the incident wave. Conversely, for $z > 1$, the reflected wave is an expansion and the transmitted wave is weaker than the incident wave. These qualitative results should be applicable within limits for shock waves. They are useful in selecting the appropriate set of equations to be solved for full-shock solutions and also in setting the limits for the intervals over which solutions are sought.

Weak-Shock Theory

To treat waves of finite strength, equation (1) must be expressed in terms of wave strengths. This is accomplished by writing the second term in equation (3) (which is an exact equation) in the form

$$\frac{\Delta p_r}{p_1} = \frac{\Delta p_r}{p_2}\frac{p_2}{p_1} = \frac{\Delta p_r}{p_2}\left(1 + \frac{p_2 - p_1}{p_1}\right) = \varepsilon_r(1+\varepsilon_i) \tag{13}$$

Equation (3) then becomes

$$\varepsilon_i + (1+\varepsilon_i)\varepsilon_r = \varepsilon_t \tag{14}$$

It is assumed that either the incident shock strength or the incident shock angle is prescribed, since each of these quantities can be directly prescribed in terms of the other. (See ref. 5, formula (128); see also subsequent eq. (26).)

The weak-wave solution can be treated as a correction to the acoustic solution. Thus, denoting the results of the acoustic solution (eq. (4)) by the subscript o, equation (2) becomes

$$\nu_i - (\nu_{r,o} + \delta\nu_r) = \nu_{t,o} + \delta\nu_t \tag{15}$$

which, by subtracting the acoustic relation, yields simply

$$-\delta\nu_r = \delta\nu_t \tag{16}$$

The second-order relation between the flow deflection angle and the wave strength is (see ref. 5, formulas (151) and (174))

$$\varepsilon = a\nu + b\nu^2 \tag{17a}$$

where

$$a = \frac{\gamma M^2}{\beta} \tag{17b}$$

$$b = \frac{\gamma M^2}{4\beta^4}[(\gamma+1)M^4 - 4\beta^2] \tag{17c}$$

The values of γ and β in these expressions are those immediately ahead of the wave. For an expansion, the deflection angle ν is negative and, consequently, the first-order term in equation (17a) becomes negative. The second-order term is identical for compression and expansion waves.

Since γ_1, γ_5, M_1, and M_5 are prescribed, a_1, b_1, a_5, and b_5 can be computed directly. In order to compute a_2 and b_2, the value of M_2 is required. It could be estimated by the weak-wave approximation (ref. 6, p. 292), but since the exact expression (ref. 5, formula (157)) is only slightly more complicated, it was used in the present study.

Substituting equations (17) into equation (14) yields

$$\begin{aligned} a_1\nu_i + b_1\nu_i^2 + \left(1 + a_1\nu_i + b_i\nu_i^2\right)(a_2\nu_r + b_2\nu_r^2) \\ = a_5\nu_t + b_5\nu_t^2 \end{aligned} \tag{18}$$

If terms higher than second-order are discarded, equation (18) becomes

$$\begin{aligned} a_1\nu_i + b_1\nu_i^2 + a_2\nu_r + a_1a_2\nu_i\nu_r + b_2\nu_r^2 \\ = a_5\nu_t + b_5\nu_t^2 \end{aligned} \tag{19}$$

Now when ν is written as a correction to the acoustic solution, as in equation (15), the correction $\delta\nu$ results from including terms of order ν^2. Thus, substituting $\nu = \nu_o + \delta\nu$ for the reflected and transmitted waves in equation (19) and again eliminating terms higher than second-order yields

$$\begin{aligned} a_1\nu_i + b_1\nu_i^2 + a_2\nu_{r,o} + a_2\delta\nu_r + a_1a_2\nu_i\nu_{r,o} \\ + b_2\nu_{r,o}^2 = a_5\nu_{t,o} + a_5\delta\nu_t + b_5\nu_{t,o}^2 \end{aligned} \tag{20}$$

Subtracting the first-order accurate relation

$$a_1\nu_i + a_2\nu_{r,o} = a_5\nu_{t,o} \tag{21}$$

yields for the second-order terms

$$\begin{aligned} a_2\delta\nu_r - a_5\delta\nu_t = b_5\nu_{t,o}^2 - b_2\nu_{r,o}^2 - b_1\nu_i^2 \\ - a_1a_2\nu_i\nu_{r,o} \end{aligned} \tag{22}$$

The interpretation of the terms in this equation is as follows. The coefficients a_2 and a_5 of the left-hand terms indicate the proportional influence of the second-order corrections on the reflected and transmitted wave strengths, respectively. The first three terms on the right result from including the nonlinear second-order term in the relation between flow angle and wave strengths. The last term represents the influence of the pressure increase through the incident wave on the strength of the reflected wave. This latter term is negative for a shock and positive for an expansion.

Now substituting $-\delta\nu_r$ for $\delta\nu_t$ from equation (16) into equation (22) yields the solution

$$\delta\nu_r = \frac{b_5\nu_{t,o}^2 - b_2\nu_{r,o}^2 - b_1\nu_i^2 - a_1a_2\nu_i\nu_{r,o}}{a_2 + a_5} \tag{23}$$

The actual flow deflection through the reflected wave is

$$\nu_r = \nu_{r,o} + \delta\nu_r \tag{24}$$

The flow deflection through the transmitted wave can now be obtained from equation (2). The strength of the reflected wave is, from equation (17a),

$$\varepsilon_r = a_2\nu_r + b_2\nu_r^2 \tag{25}$$

and ε_t is then obtained from equation (14).

Exact Shock Relations

To solve the exact equations for the flow quantities in regions 3 and 4 requires a numerical procedure. The specific formulas used in the procedure depend on the nature of the reflected wave (compression or expansion) and also on the flow parameters that are specified. Any fundamental quantity relating to the reflected or transmitted waves or to the flow in regions 3 or 4 may be chosen as the unknown parameter to be solved for in the numerical procedure. For the following calculations, ε_r was chosen for the unknown parameter if the reflected wave was a compression, but M_3 was found to be a more convenient parameter to solve for if the reflected wave was an expansion.

Reflected compression. For the former case (reflected compression) the following method was used. The quantities M_1, M_5, γ_1, γ_5, p_1, p_5, and either ε_i or θ_i are assumed to be given. If θ_i rather than ε_i is specified, then ε_i is computed from the formula (ref. 5, formula (128))

$$\varepsilon = \frac{2\gamma M^2 \sin^2\theta - (\gamma - 1)}{\gamma + 1} \tag{26}$$

Note that here ε corresponds to $\xi - 1$ in reference 5. The Mach number in region 2 is obtained from the relation (ref. 5, formula (157))

$$M_2^2 = \frac{M_1^2[(\gamma+1)\varepsilon + 2\gamma] - 2\varepsilon(\varepsilon+2)}{(1+\varepsilon)[(\gamma-1)\varepsilon + 2\gamma]} \tag{27}$$

It is assumed that the value of γ does not change through the shock (although different values of γ may exist on the two sides of the slipstream). The flow deflection ν_i due to the incident shock is determined by (ref. 5, formula (160))

$$\tan\nu = \left(\frac{\varepsilon}{\gamma M^2 - \varepsilon}\right)\sqrt{\frac{2\gamma(M^2-1) - (\gamma+1)\varepsilon}{(\gamma+1)\varepsilon + 2\gamma}} \tag{28}$$

Thus, the required quantities in region 2 are computed directly without iteration. Equation (28) also yields a relation

$$\nu_r = \nu_r(M_2, \varepsilon_r) \tag{29}$$

The transmitted wave strength ε_t is now expressed in terms of ε_r by equation (14). Equation (28) is then used to determine $\nu_t = \nu_t(M_5, \varepsilon_t)$. But with ε_t replaced by $\varepsilon_t(\varepsilon_r)$ and with $\gamma = \gamma_5$, this relation becomes a function of ε_r

$$\nu_t = \nu_t(M_5, \varepsilon_r) \tag{30}$$

Finally, substituting the functions in equations (29) and (30) into equation (2) yields a single equation for the unknown parameter ε_r, which is determined numerically as a zero of the function

$$f(\varepsilon_r) = \nu_i - \nu_r(\varepsilon_r) - \nu_t(\varepsilon_r) \tag{31}$$

From the value of ε_r thereby obtained, ε_t is found from equation (14), and the reflected and transmitted shock angles are found by solving equation (26) for θ. It is not necessary to determine the flow deflection angles now, since they are computed at each step in the numerical procedure and written over at the subsequent step. Thus, the final values stored in these locations when the procedure has converged are the correct values.

Reflected expansion. When the reflected wave is an expansion, it is convenient to choose for the unknown parameter the Mach number in region 3 M_3; then the relation (ref. 5, formula (44))

$$\frac{p}{p_T} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma}{\gamma-1}} \tag{32}$$

is applied as follows. First, using the known values of p_2 and M_2 (eq. 27)), equation (32) is solved for $p_{T,2}$. Then, since $p_{T,3} = p_{T,2}$ for a reflected expansion, equation (32) determines p_3 as a function of M_3. The flow deflections, in expanding from $M = 1.0$ to M_2 and from $M = 1.0$ to M_3, are calculated from the relation (ref. 5, formula (173b))

$$\nu = \sqrt{\frac{\gamma+1}{\gamma-1}}\tan^{-1}\sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)} - \cos^{-1}\frac{1}{M} \tag{33}$$

The difference of these two calculations is $\nu_r(M_3)$. Now $p_3(M_3)$ is calculated by equation (32) and, since p_2 is known, ε_r can be calculated. Substituting this value into equation (14) yields $\varepsilon_t(M_3)$. The flow deflection ν_t associated with the transmitted shock is then calculated as a function of M_3 by equation (28). Finally, the value of M_3 is determined numerically as the zero of the function

$$g(M_3) = \nu_i - \nu_r(M_3) - \nu_t(M_3) \tag{34}$$

The remaining flow variables can now be calculated by substituting this value of M_3 back into the previous relations.

Computed Examples

Several sample calculations were performed for the purpose of comparing the acoustic, weak-wave, and exact solutions. The results of the calculations are displayed in figures 2 and 3. For the weak-wave and exact solutions, the reflection and transmission coefficients are defined by

$$R \equiv \frac{\varepsilon_r}{\varepsilon_i} \tag{35}$$

$$T \equiv \frac{\varepsilon_t}{\varepsilon_i} \tag{36}$$

Equations (6) and (7) for the acoustic case are consistent with these definitions since the acoustic pressure amplitudes are all referred to the undisturbed pressure p_1 ($= p_5$), and dividing both numerator and denominator by this quantity does not change the ratio.

The results demonstrate that, for all the examples, the weak-shock solution is an improvement over the acoustic approximation, and in most cases it is remarkably accurate. In all cases for which the reflected wave is an expansion or a very weak shock, the weak-wave results are significantly better than those for a reflected shock of strength comparable with that of the incident shock. (Compare figs. 2(h)—(k).) This indicates that, although the entropy increase is third order in shock strength, the effect of the entropy variation is noticeable. The approximate theories also yield poor results when the local Mach number falls into the highly nonlinear region near $M = 1$. (See fig. 2(a), where $M_4 \rightarrow 1$.)

Counterflowing Streams

References 1 and 2 observe that strong amplifications of the reflected and transmitted waves are possible if the streams separated by the interface are flowing in opposite directions. It is difficult to imagine a practical steady-state situation for which two supersonic streams would be counterflowing. One can, however, conceive of several situations for which such a phenomenon might occur on a transient basis. One possibility would be a shock wave, emitted by a passing airplane or from a blast, incident on a supersonic jet. Figure 4 depicts such a possibility.

Suppose, for example, the jet emerges at $M = 3$ relative to the ambient air, and an airplane is flying in the jet flow direction at $M = 1.6$ so that the shock that it generates is incident on the jet. Then, relative to a coordinate system moving with the point of interaction at the interface, there is a $M = 1.6$ flow moving toward the left above the interface and (assuming the same sound speed in the jet as in the ambient air) a $M = 1.4$ flow moving toward the right below the interface.

The acoustic analysis (refs. 1 and 2) of this problem is straightforward. The Mach number of one of the flows is simply indicated to be negative and the parameter z in equation (9) is also determined to be negative. Then, the denominators in the expressions for the reflection and transmission coefficients (eqs. (11) and (12)) can become very small and therefore yield large values for the reflected and transmitted wave amplitudes. However, it should be mentioned that this analysis rapidly becomes inconsistent, since large amplitude acoustic waves propagate nonlinearly and develop into shock waves, which are governed by a different set of boundary equations. For these equations one should assume that the free-stream conditions γ_1, M_1, γ_4, and M_4 (fig. 4(b)) are prescribed, as well as the strength ε_1 of the incident shock. However, at the interface, upstream influences always occur since each stream is flowing upstream relative to the other. Thus, a flow angularity can develop ahead of both incident and reflected shocks, and consequently, the problem is not well-posed.

However, if one simply proceeds formally, the pressure relation at the interface becomes

$$\frac{p_2 - p_1}{p_1} + \frac{p_3 - p_2}{p_2}\frac{p_2}{p_1} = \left(\frac{p_5 - p_4}{p_4}\right)\frac{p_4}{p_5} \tag{37a}$$

or

$$\varepsilon_i + (1 + \varepsilon_i)\varepsilon_r = -\frac{\varepsilon_t}{1 + \varepsilon_t} \tag{37b}$$

or, since

$$\frac{p_2}{p_1}\frac{p_3}{p_2} = (1 + \varepsilon_i)(1 + \varepsilon_r) = \frac{1}{1 + \varepsilon_t} = \frac{p_4}{p_5}$$

$$\varepsilon_i + (1 + \varepsilon_i)\varepsilon_r = -(1 + \varepsilon_i)(1 + \varepsilon_1)\varepsilon_t \tag{37c}$$

Equation (37b) or (37c) may be compared with the simpler equation (14) for the coflowing case.

A weak-wave analysis of this problem would hardly be justified inasmuch as the problem, as noted, is not well-posed, it is largely academic, and the weak-wave theory loses accuracy for strong reflected shocks.

Concluding Remarks

A weak-wave analysis of shock interaction with a slipstream has been presented. The theory was compared with the acoustic theory and the exact nonlinear analysis. Sample calculations indicated that the weak-wave theory represented a good approximation to the exact solution when the shock waves are sufficiently weak that the associated entropy increase is negligible. A qualitative discussion of the case of counterflowing streams was also included.

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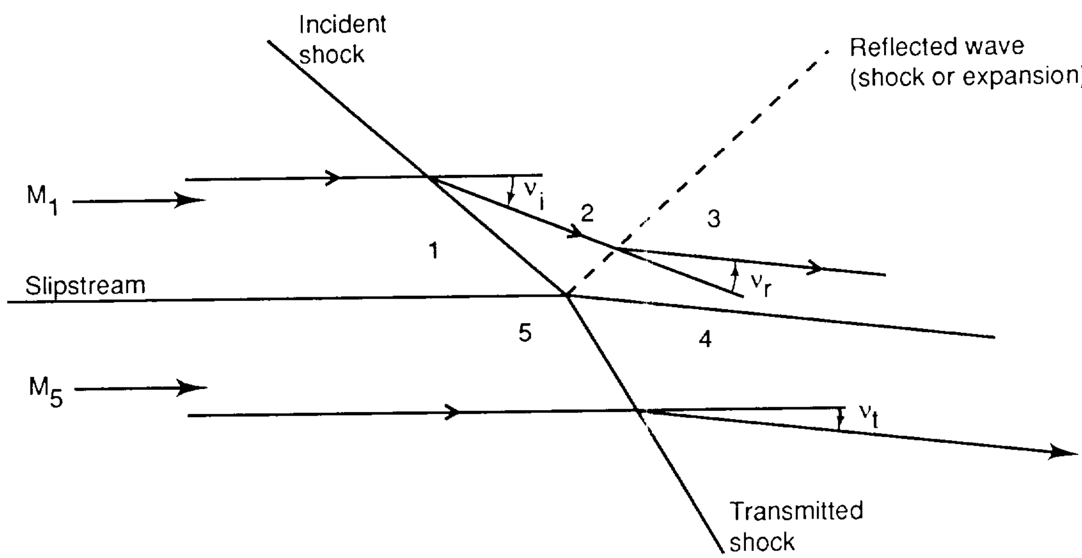
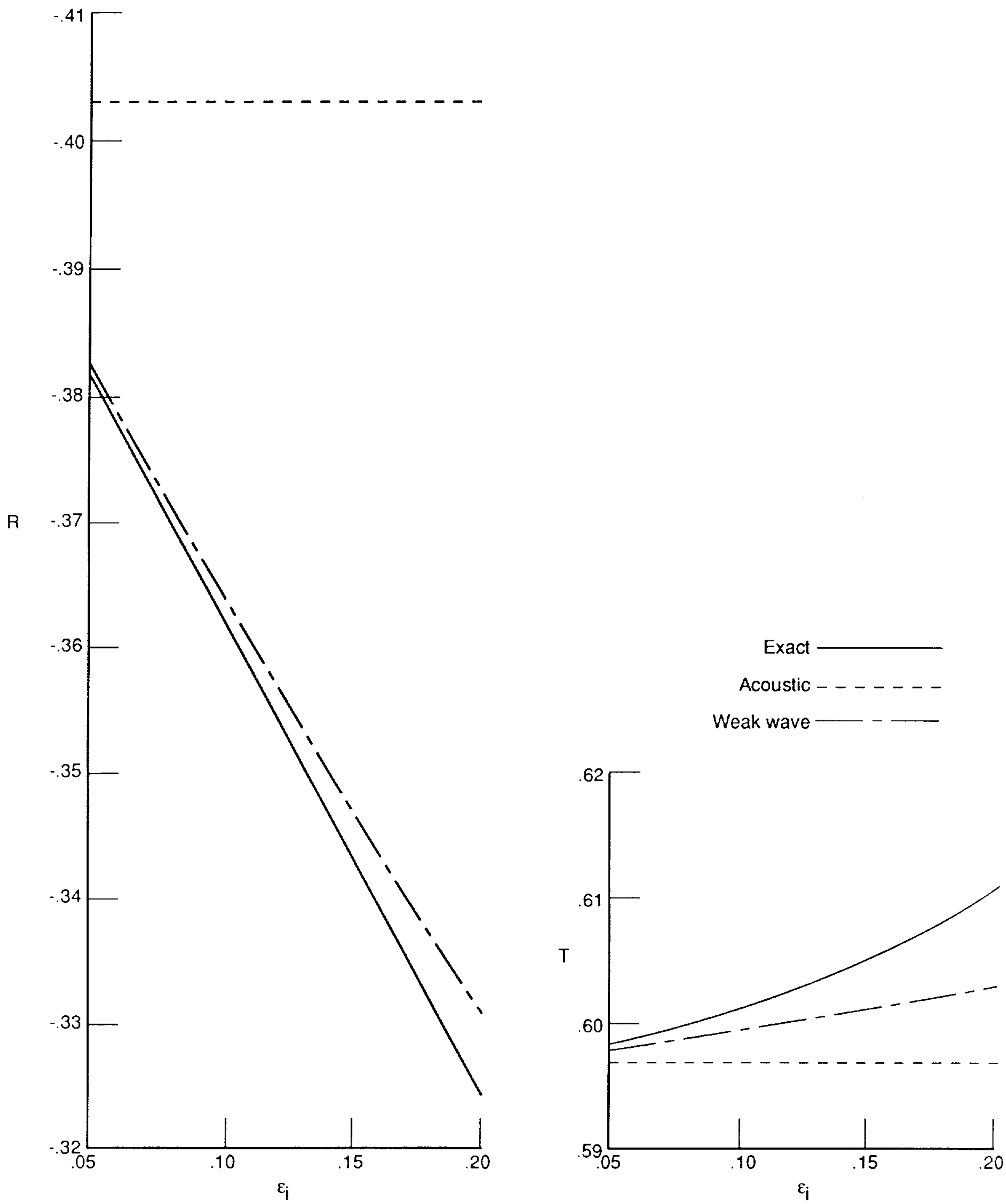
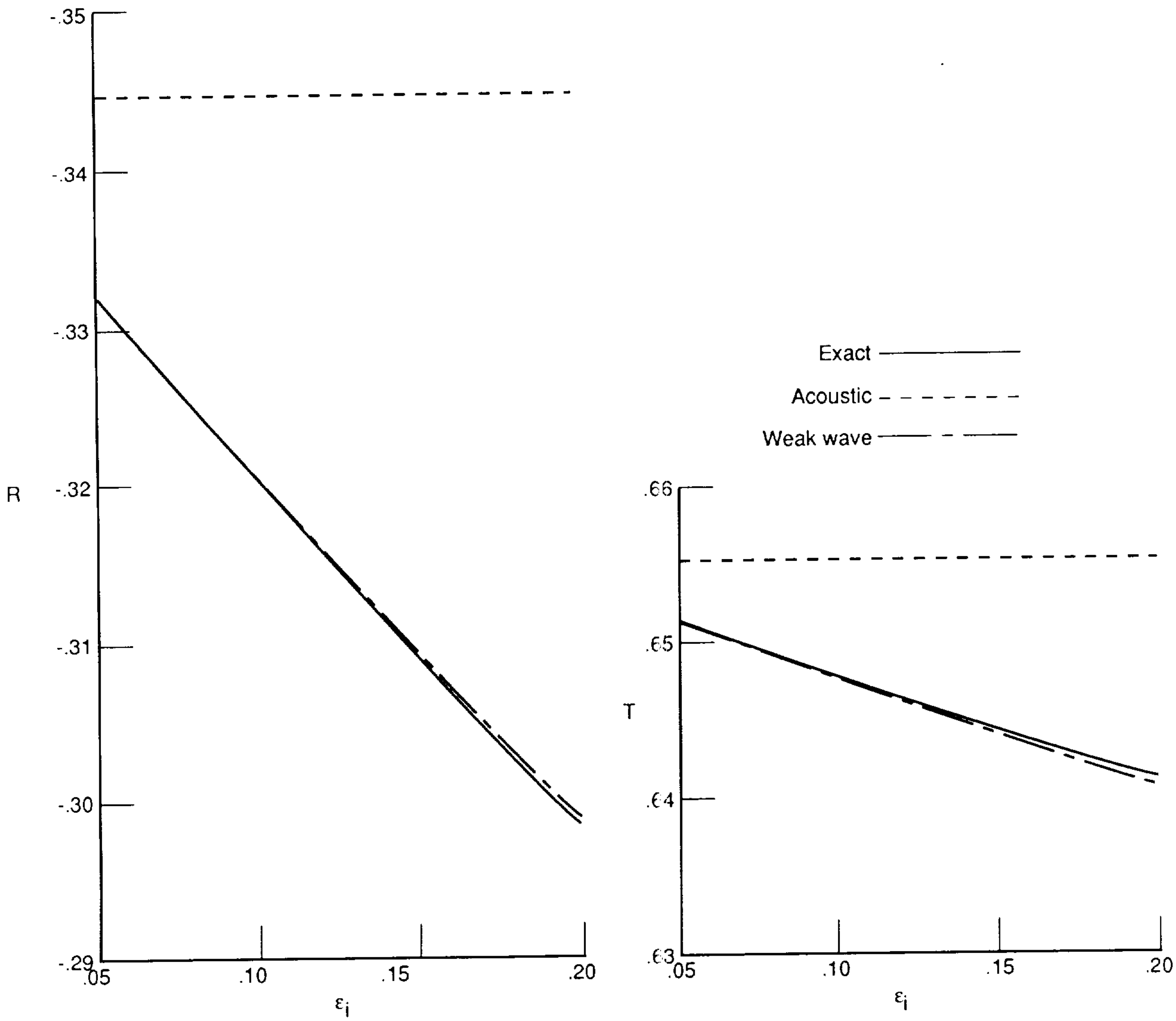


Figure 1. Diagram of shock-slipstream interaction.



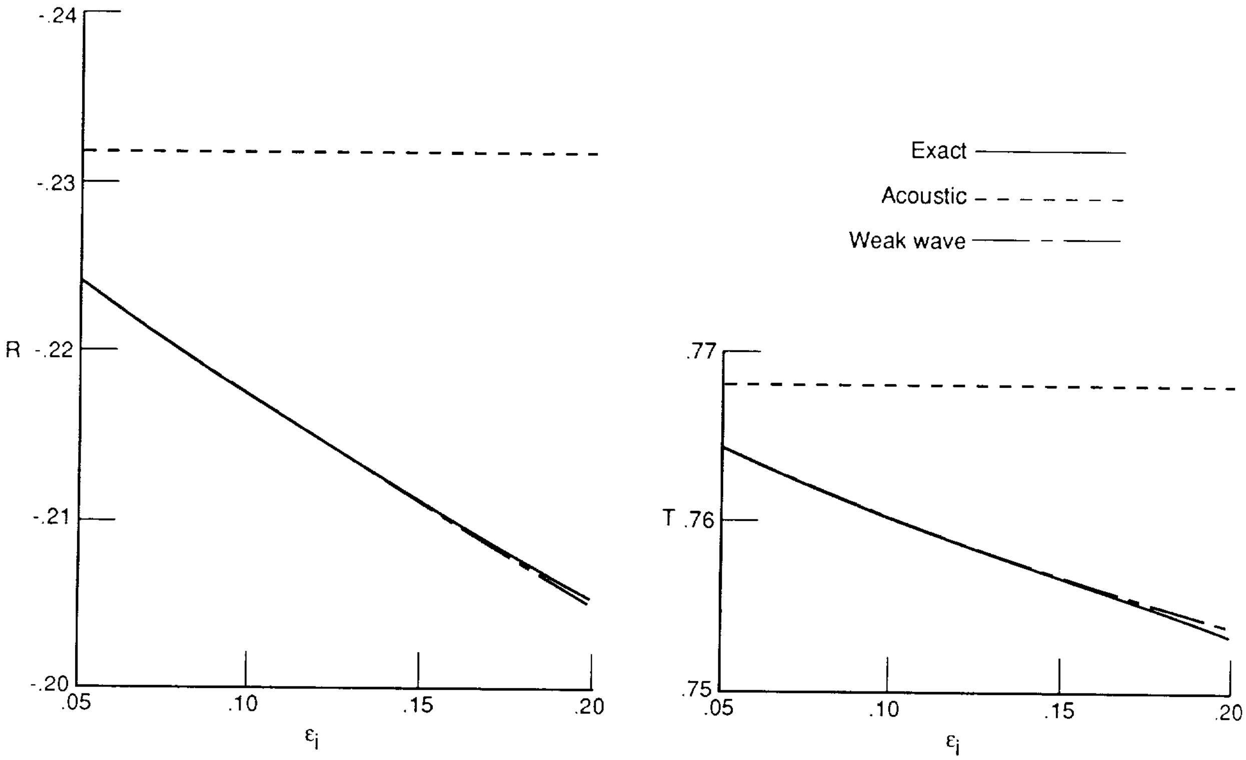
(a) $M_1 = 5.0$; $M_5 = 1.2$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 2.351$).

Figure 2. Sample calculations of $R\left(\frac{\varepsilon_r}{\varepsilon_i}\right)$ and $T\left(\frac{\varepsilon_t}{\varepsilon_i}\right)$.

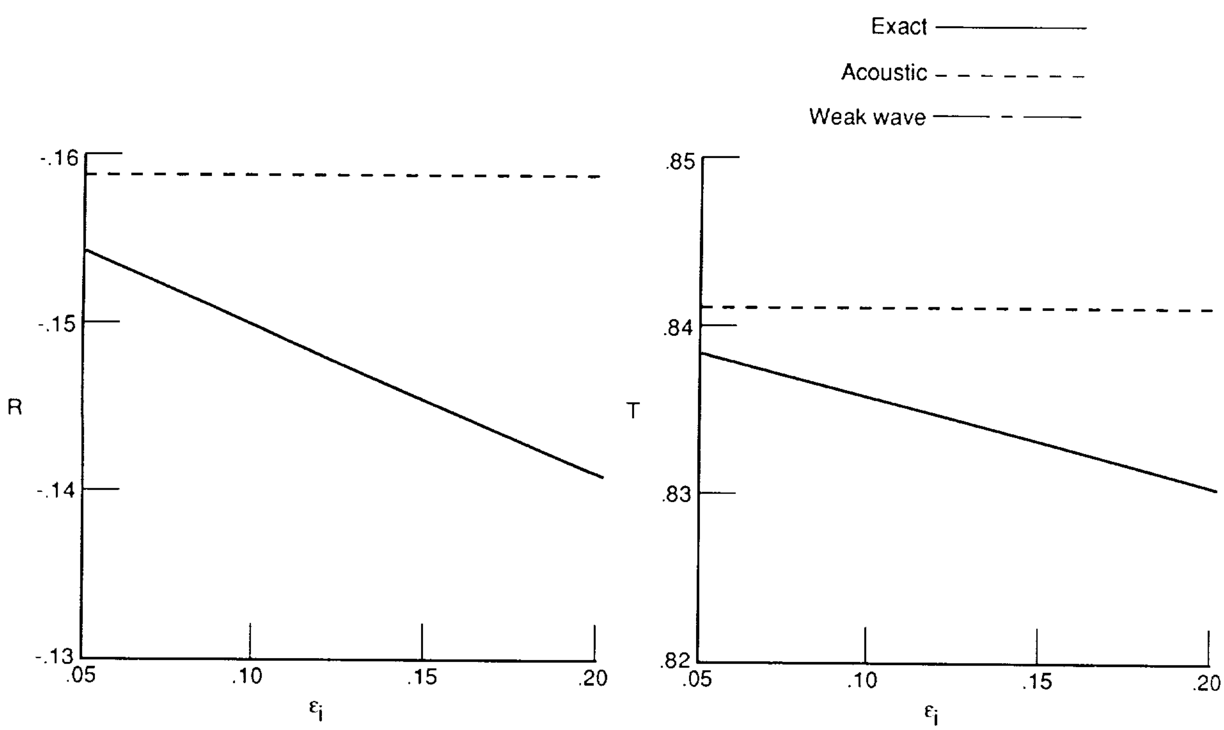


(b) $M_1 = 4.0$; $M_5 = 1.5$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 2.053$).

Figure 2. Continued.

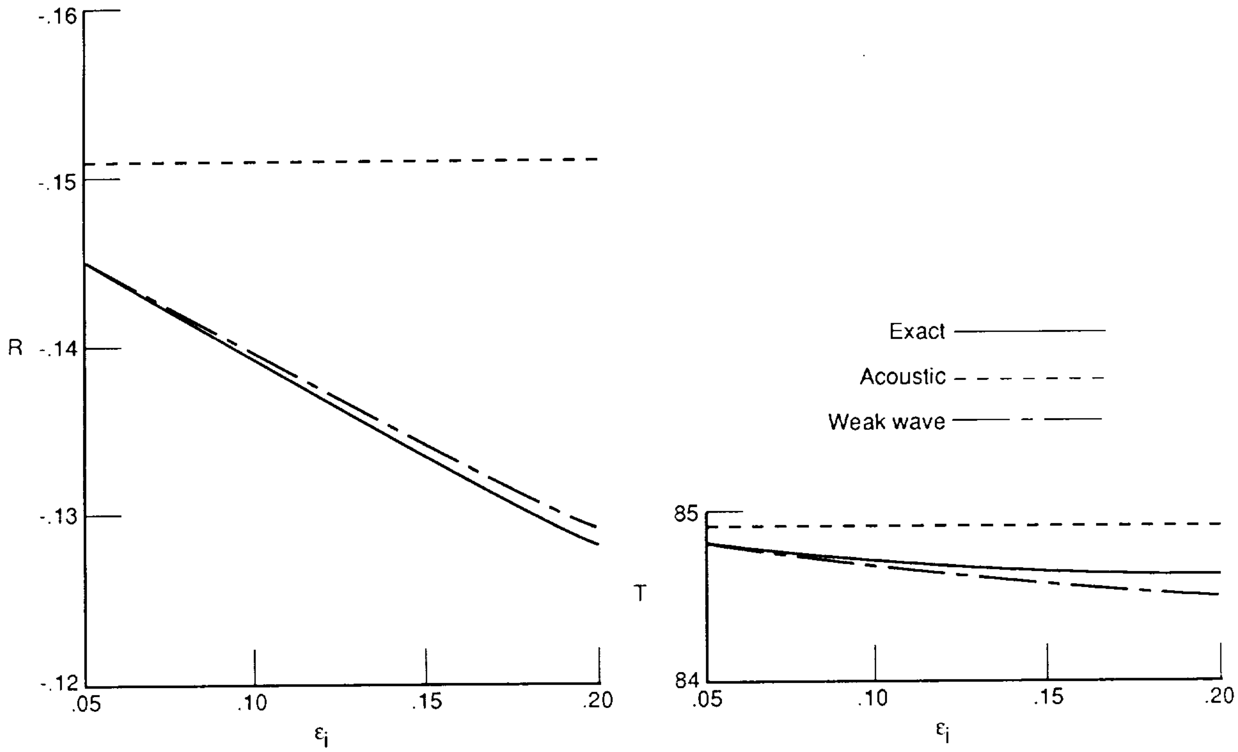


(c) $M_1 = 5.0$; $M_5 = 3.0$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 1.604$).

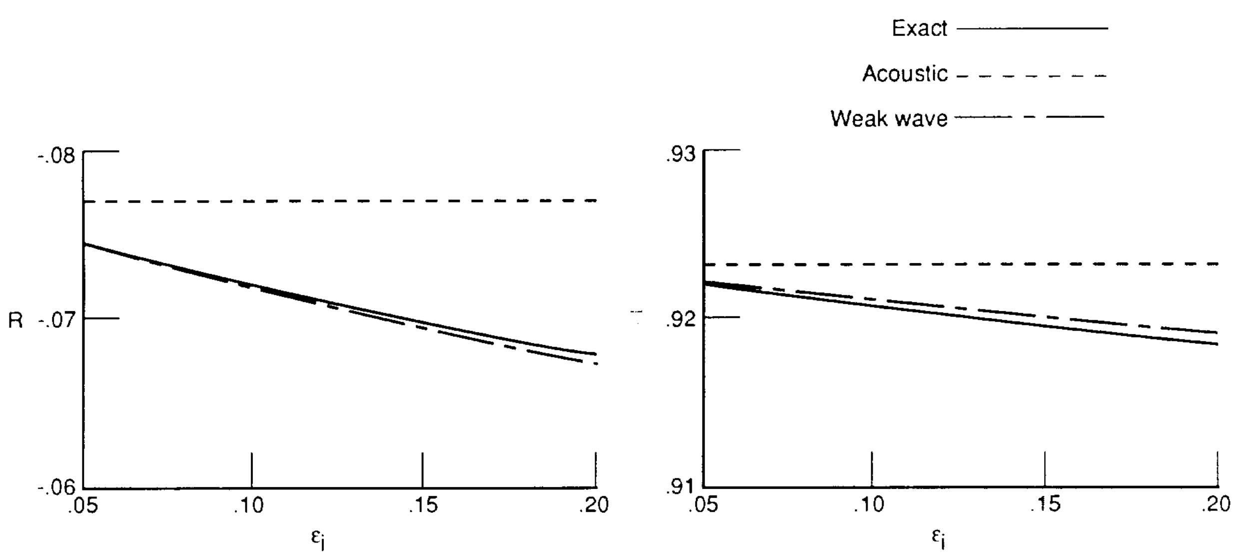


(d) $M_1 = 3.0$; $M_5 = 2.0$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 1.378$). Exact and weak-wave results are virtually indistinguishable for this case.

Figure 2. Continued.

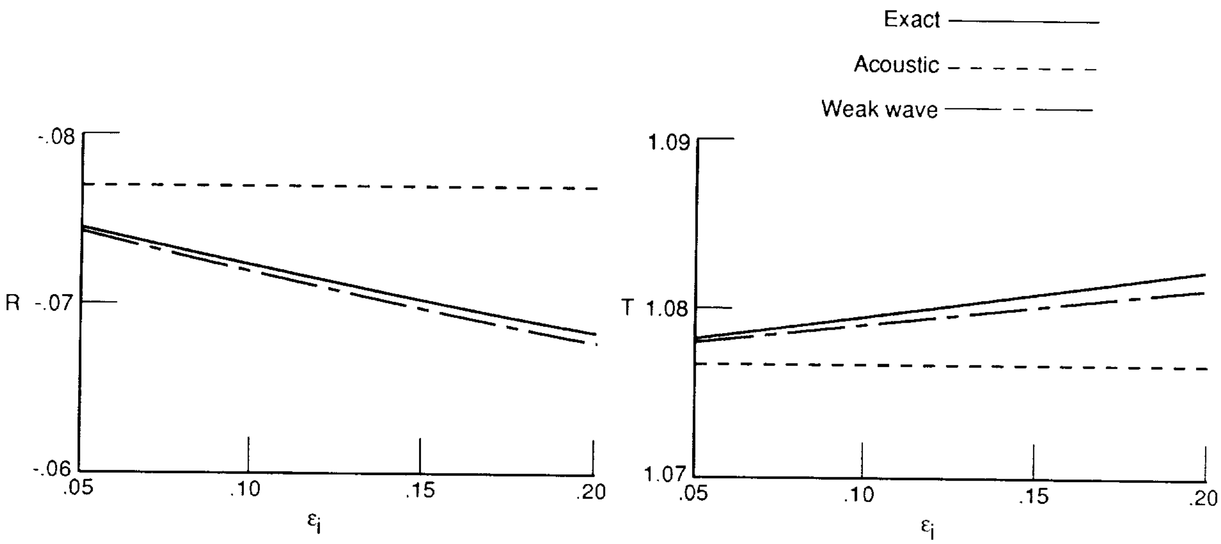


(e) $M_1 = 2.5$; $M_5 = 1.5$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 1.355$).

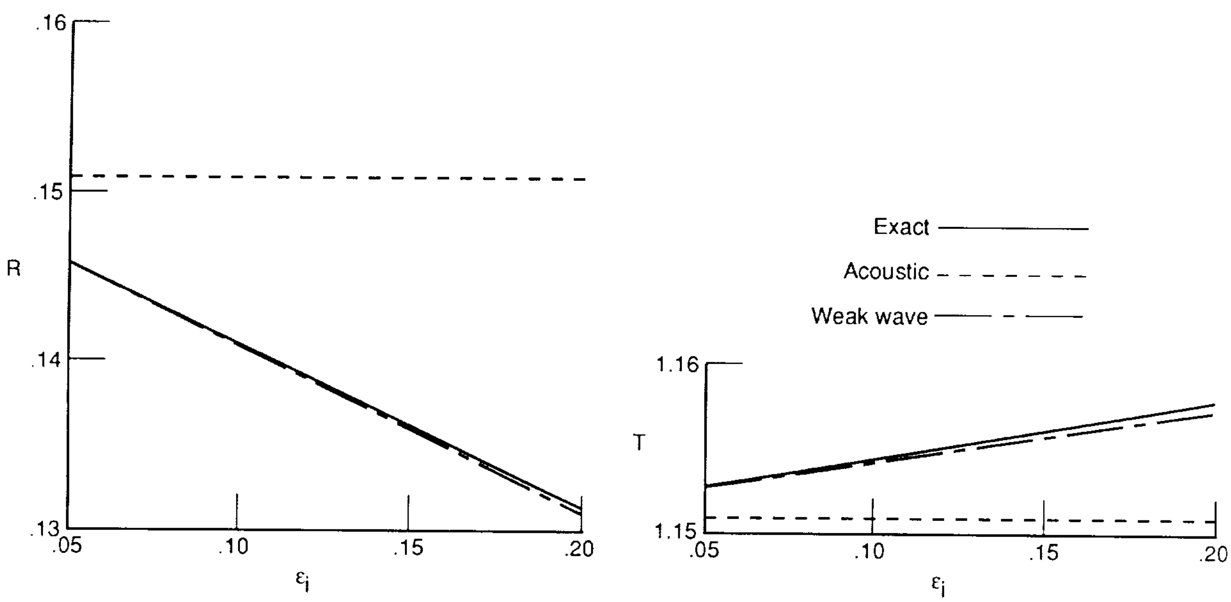


(f) $M_1 = 2.0$; $M_5 = 2.0$; $\gamma_1 = 1.4$; $\gamma_5 = 1.2$ ($z = 1.167$).

Figure 2. Continued.

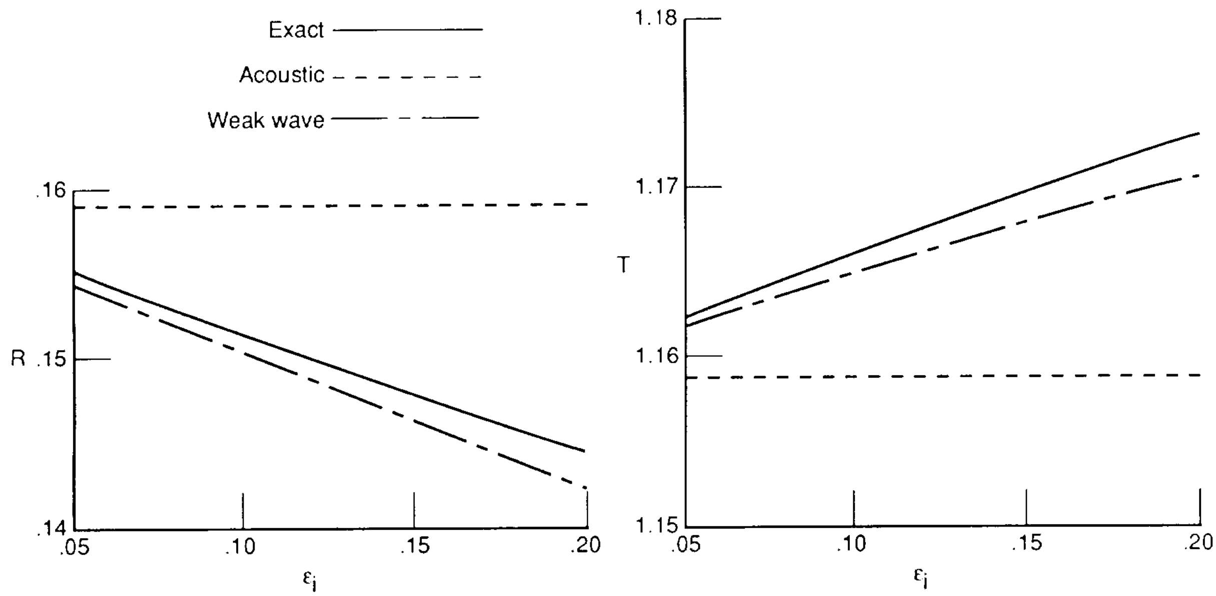


(g) $M_1 = M_5 = 2.0$; $\gamma_1 = 1.2$; $\gamma_2 = 1.4$ ($z = 0.8571$).

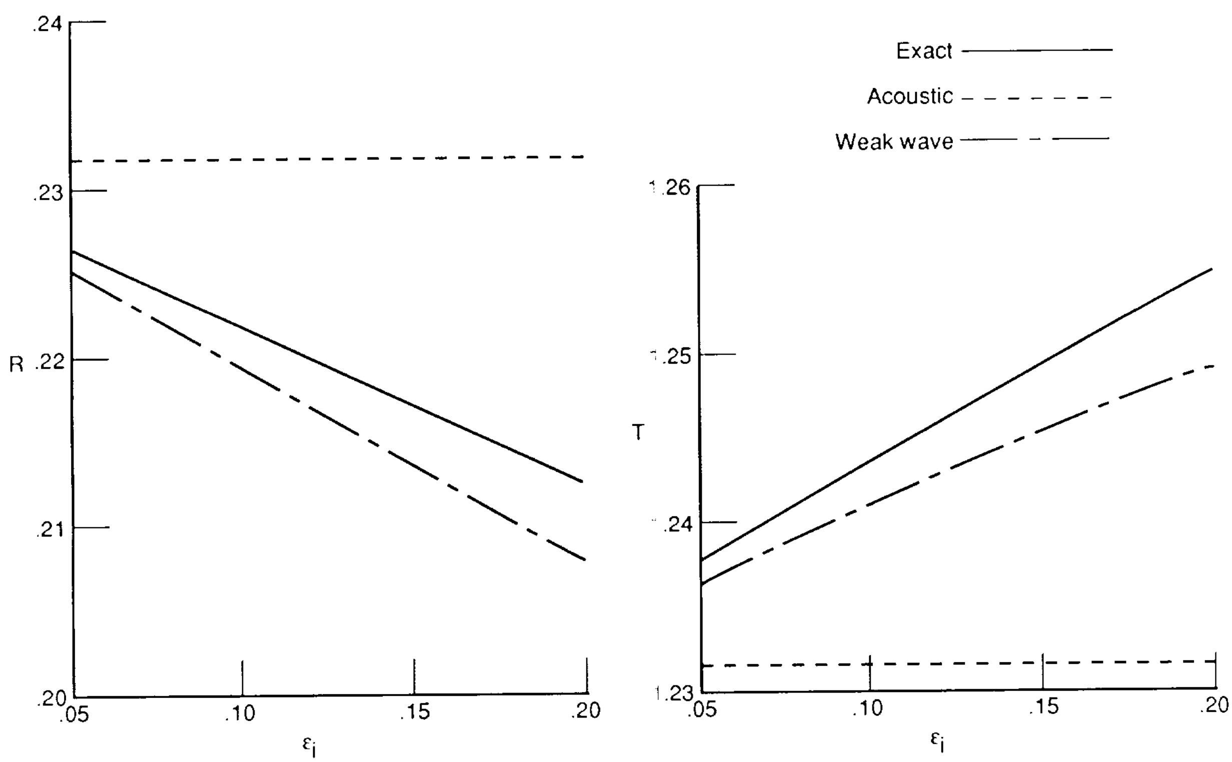


(h) $M_1 = 1.5$; $M_5 = 2.5$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 0.738$).

Figure 2. Continued.

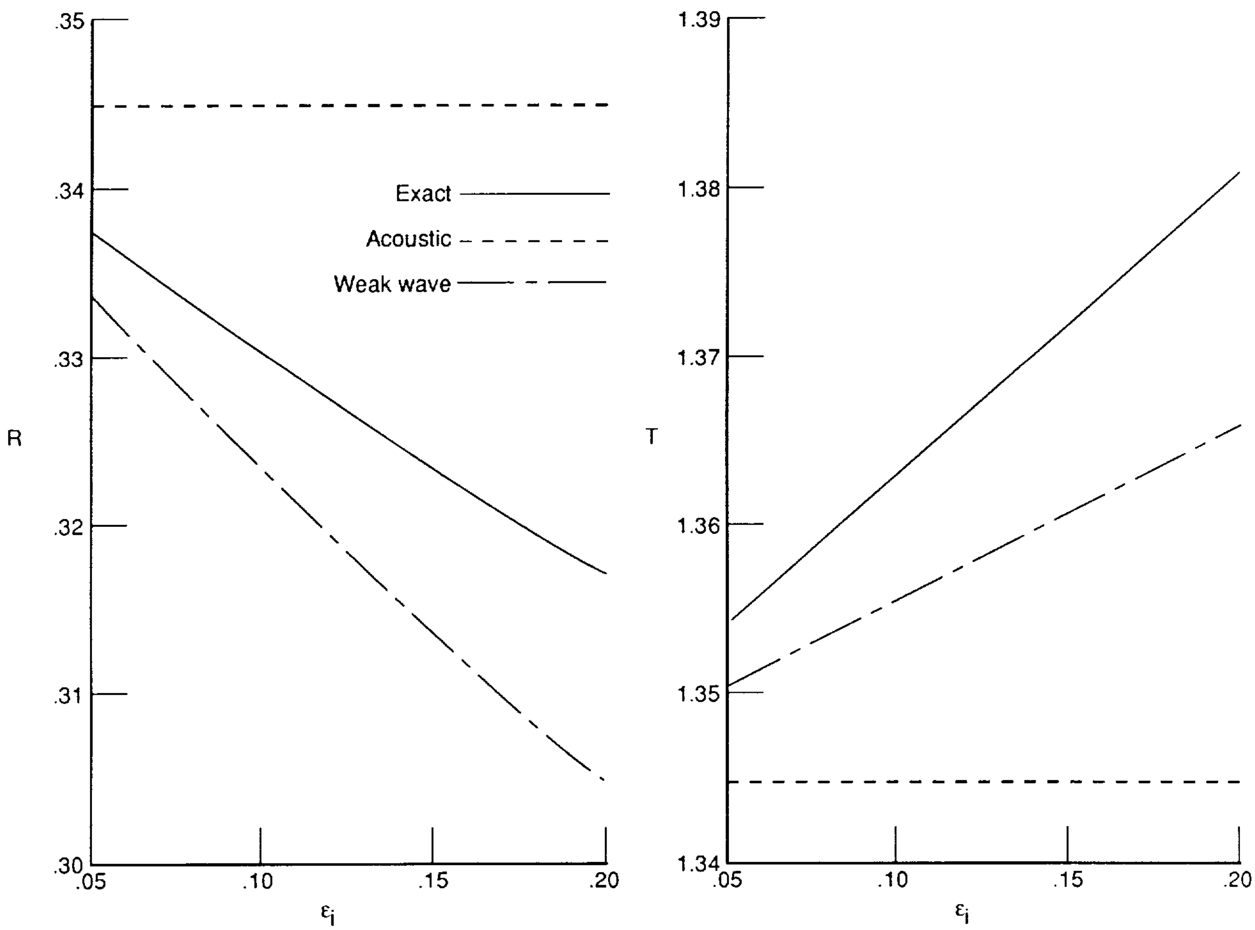


(i) $M_1 = 2.0$; $M_5 = 3.0$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 0.726$).



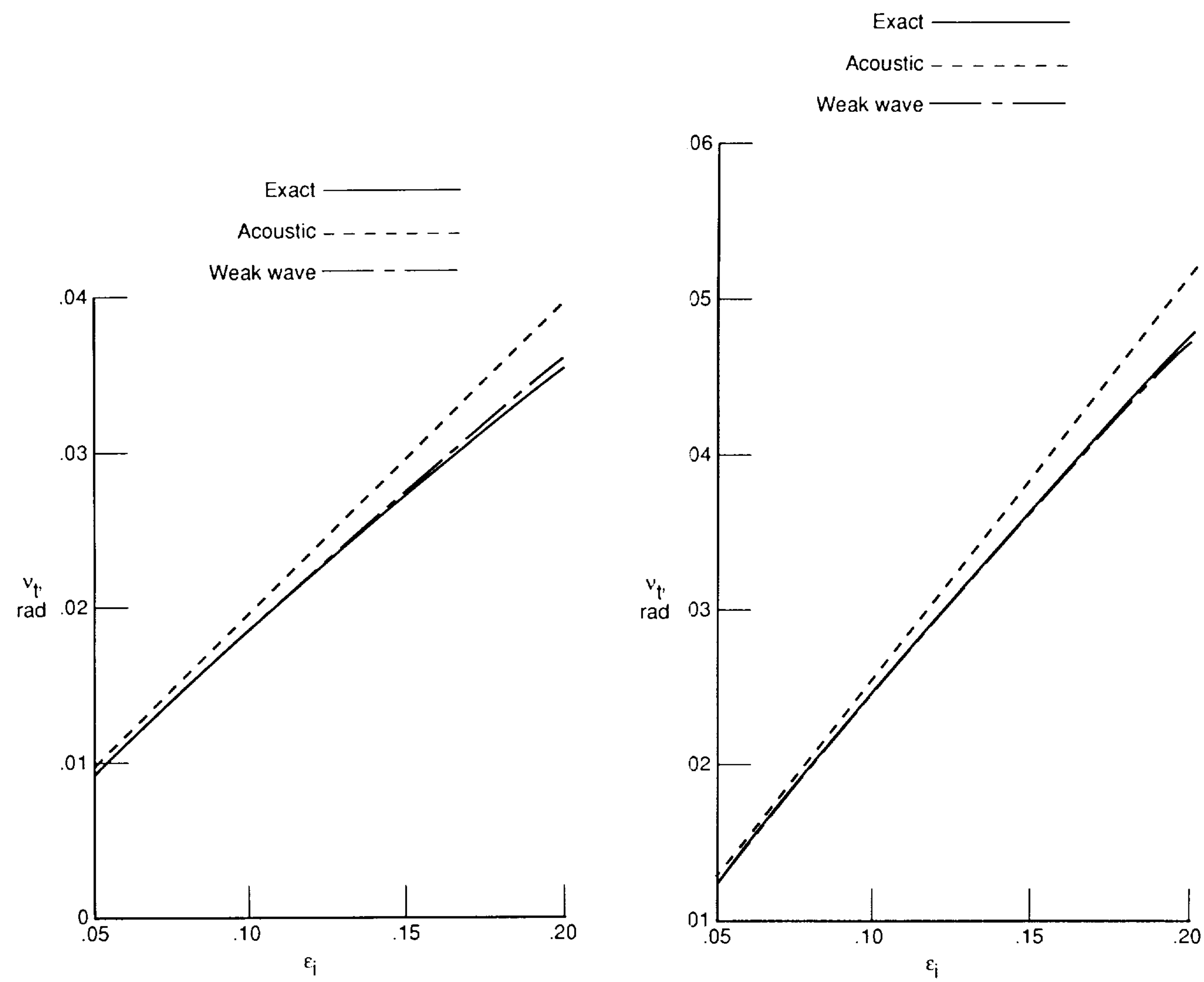
(j) $M_1 = 3.0$; $M_5 = 5.0$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 0.6235$).

Figure 2. Continued.



(k) $M_1 = 1.5$; $M_5 = 4.0$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 0.487$).

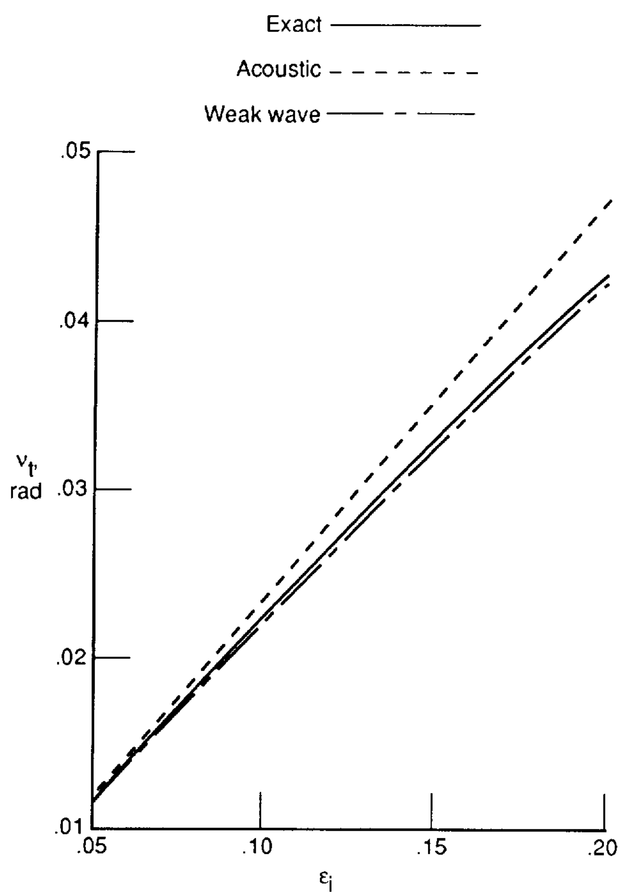
Figure 2. Concluded.



(a) $M_1 = 5.0$; $M_5 = 1.2$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 2.351$).

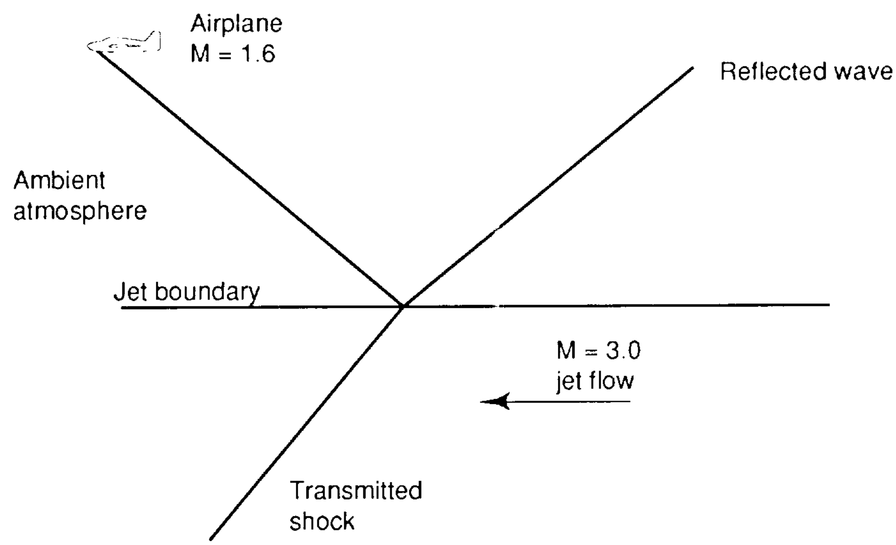
(b) $M_1 = 2.0$; $M_5 = 3.0$; $\gamma_1 = \gamma_5 = 1.4$ ($z = 0.726$).

Figure 3. Typical results for total flow deflection $\nu_t = \nu_i + z$.

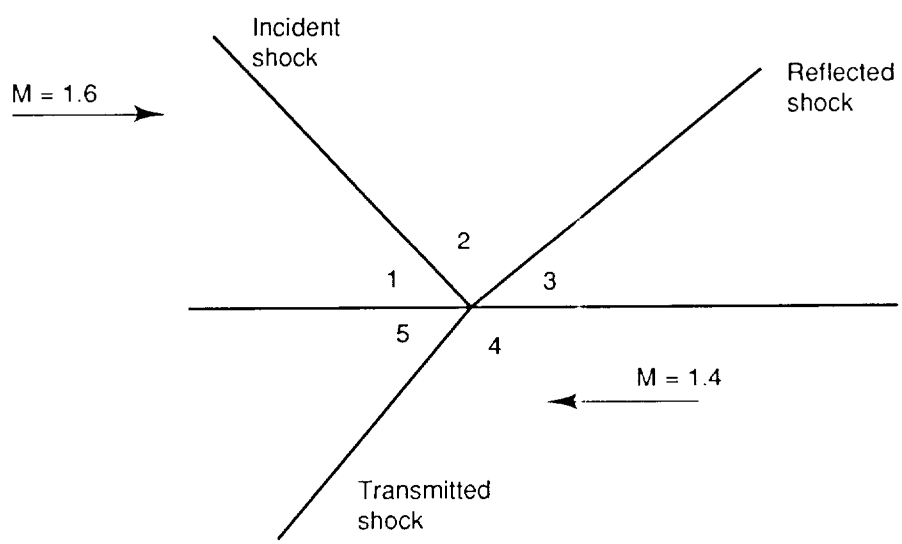


(c) $M_1 = 1.5$; $M_5 = 4.0$; $\gamma_1 = \gamma_5 = 1.4$ $(z = 0.487)$.

Figure 3. Concluded.



(a) Shock configuration with interaction point moving along jet boundary.



(b) System of figure 4(a) in coordinate system moving with interaction point.

Figure 4. Transient phenomenon giving rise to counterflow situation. Sound speed in jet assumed to be equal to that in ambient air.

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16. Abstract

A weak-wave analysis of shock interaction with a slipstream is presented. The theory is compared with the acoustic theory and the exact nonlinear analysis. Sample calculations indicate that the weak-wave theory yields a good approximation to the exact solution when the shock waves are sufficiently weak that the associated entropy increase is negligible. A qualitative discussion of the case of counterflowing streams is also included.

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